Self-Powered Microthermionic Converter

Albert C. Marshall
18 Meadow View Rd.
Sandia Park, NM 87047

Donald B. King
13000 Summer NE
Albuquerque, NM 87112

Kevin R. Zavadil
419 El Valle Serrano
Bernalillo, NM 87004

Stanley H. Kravitz
26 Aspen Rd.
Placitas, NM 87043

Chris P. Tigges
8415 Gordon Snidow Ct. NE
Albuquerque, NM 87122

Gregory A. Vawter
9805 Admiral Nimitz NE
Albuquerque, NM 87111

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CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation-in-part application of U.S. Patent Application Serial No. 09/895,350 entitled "Microminiature Thermionic Converters," to King, et al., filed on June 27, 2001; U.S. Patent Application Serial No. 09/895,759 entitled "Thermionic Modules," to King, et al., filed on June 27, 2001; U.S. Patent Application Serial No. 09/895,372 entitled "Chemical Vapor Deposition Techniques and Related Methods for Manufacturing Microminiature Thermionic Converters," to King, et al., filed on June 27, 2001 ; and U.S. Patent Application Serial No. 09/257,336 entitled "Low Work Function Materials for Microminiature Energy Conversion and Recovery Applications," to Zavadil, Ruffner, and King, filed on February 25, 1999. This application is related to U.S. Patent 6,294,858 to King., et al., and to co-pending applications "Micro Heat Barrier" and "Methods for Fabricating a Micro Heat Barrier", by Marshall, et al. The specifications thereof of all of the above are incorporated herein by reference.

GOVERNMENT RIGHTS

The Government has rights to this invention pursuant to Contract No. DE-AC04-94AL85000 awarded by the U.S. Department of Energy.

BACKGROUND OF THE INVENTION

The present invention relates to microthermionic self-powered converters having high energy conversion efficiencies and to methods of manufacturing those converters using micromachining manufacturing techniques.

Thermionic generators were first proposed in 1915 by Schlichter, but many of the theoretical problems that existed at the inception of the idea persist today. Thermionic generators convert heat energy to electrical energy by an emission of electrons from a heated emitter electrode. The electrons flow from the emitter electrode, across an interelectrode gap, to a collector electrode, through an external load, and return back to

the emitter electrode, thereby converting the heat energy to electrical energy. Historically, voltages produced are low, and the high temperature required to produce adequate current has produced numerous problems in maintaining the devices, including the unintended transfer of heat from the heated emitter electrode to the cold collector electrode. Practical thermionic conversion was demonstrated in 1957 by Hernquist in which efficiencies of 5-10% were reached with power densities of 3-10 W/cm^2. Generally, such efficiencies and power densities were not sufficient to be financially competitive in the energy market, thus reducing the application of such devices. Furthermore, such devices were too large for use as miniaturized electrical power sources.

Another problem, "space-charge effect," is described by Edelson (U.S. Pat. No. 5,994,638). A space-charge effect results when the build up of negative charge in the cloud of electrons between the two electrodes deter the movement of other electrons toward the collector electrode. Edelson cites two well-known methods for mitigating the space-charge effect: (1) reducing the spacing between electrodes to the order of microns, or (2) introducing positive ions into the electron cloud in front of the emitter electrode.

Introducing positive ions into the electron cloud in front of the emitter electrode generally consists of filling the interelectrode gap with an ionized gas. Thermionic converters with gas in the interelectrode gap are designed to operate with such ionized species, typically utilizing cesium vapor. Utilization of a cesium vapor results in a space charge neutralization, effectively eliminating the detrimental deterrence of electron flow. Cesium also plays a dual role by decreasing the work function of the device, i.e. the rate of electrons leaving a surface, by absorbing onto the emitter and collector surfaces, thereby allowing greater electron emission. However, too great of a pressure of cesium in the interelectrode gap will cause excess collisions between cesium atoms and electrons leaving the emitter electrode, reducing the efficiency of conversion. Therefore, a careful, complex balance must be maintained in a cesium vapor system. The current apparatus bypasses the complexities and efficiency losses

of such a system (and its related expense) by lowering the space-charge effect through reduction of spacing between electrodes to the order of microns (i.e., 1-10 microns).

Reducing the spacing between electrodes to the order of microns has proved impractical with conventional manufacturing techniques. Fitzpatrick (U.S. Patent No. 4,667,126) teaches "maintenance of such small spacing with high temperatures and heat fluxes is a difficult if not impossible technical challenge." The present invention overcomes the difficulty of reducing spacing by microengineering. U.S. Patent 6,294,858 to King, et al., "Microminiature Thermionic Converters", which is hereby incorporated herein by reference, discloses a microminiature thermionic convertor having a 1 micron electrode gap manufactured by integrated circuit (IC) semiconductor techniques. U.S. Patent 6,229,983 to Edelson, "Thermionic Convertor", also discloses a microminiature thermionic convertor fabricated using MEMS techniques. Both King's device and Edelson's device are powered by an external source of heat; not by an internal, self-contained power source, as in the present invention.

Earlier thermionic converters relied on external heat sources (nuclear power, geothermal energy, solar energy, fossil fuel combustion, wood or waste combustion), which may not be readily available to a user especially if electricity is desired in powering a mobile miniature device.

The present invention, in contrast, with its incorporated thermal source, overcomes the very modern problem of mobility and also provides more choices for operating devices that do not necessarily need to be mobile. For example, devices that are fixed, but may need to be used in a limited space may not be able to harness the thermal energy sources used by earlier devices.

SUMMARY OF THE INVENTION

The apparatus of the present invention is a self-powered microthermionic converter. A preferred embodiment of the converter comprises an emitter electrode and a collector electrode, separated by a micron-scale spaced interelectrode gap, a self-contained (i.e., incorporated, integral) thermal power source in good thermal

contact with the emitter electrode, and an electrical circuit connecting the collector electrode and emitter electrode through an external electrical load.

The interelectrode gap of a preferred embodiment is preferably less than about 10 μm, more preferably, between approximately 1μm and 10μm, and most preferably, between approximately 1μm and 3 μm. The interelectrode gap preferably comprises a vacuum. Alternate embodiments utilize cesium (or barium) vapor at a low vapor pressure, unlike the more common high vapor pressure cesium systems utilized in prior art inventions. The proposed alternate configuration, using low pressure cesium, differs from a Knudsen diode in that a small quantity of cesium is sealed into the present device during manufacture, whereas the Knudsen diode requires an external source of cesium (i.e., a cesium source apparatus).

A radioactive isotope can be used as the "self-powered" thermal power source, such as alpha-emitting Curium-242, Curium-244, or Polonium-210. Alpha particles emitted from the isotope deposit their energy (heat) within the body of the isotope if the range of the alphas is much smaller than the physical dimensions of the body (e.g., the range of a 6 MeV alpha particle is about 13 microns in copper). If the body of the isotope is very well thermally insulated, then the deposited heat can raise the temperature to very high values, greater than 600 C.

The collector electrode and emitter electrode of the converter are preferably formed by depositing or growing at least one layer of thermionic electron emissive material on a substrate. The thermionic electron emissive material is preferably an alkaline earth oxide in combination with a refractory metal. Thermionic emissive materials can be selected from barium oxide, calcium oxide and strontium oxide; combinations of these oxides; along with additions of aluminum and scandium oxides, as adjunct oxides. The preferable refractory metal to incorporate into the electron emissive oxide is tungsten, but could also include rhenium, osmium, ruthenium, tantalum, and iridium, or any combination of these metals. Tungsten, rhenium, osmium, ruthenium and iridium, or any combination of these metals can also be used as terminating (capping) top layers on the oxide or mixed oxide/metal layer. Alternately,

low-pressure alkali or alkaline earth metals, such as cesium and barium, can be used with a high work function metal like tungsten, tantalum, rhenium, osmium, ruthenium, molybdenum, iridium and platinum, or any combination of these metals. The oxides of like tungsten, tantalum, rhenium, osmium, ruthenium, molybdenum, iridium and platinum, or any combination of these metals can also be used with low-pressure alkali or alkaline earth metals, such as cesium and barium.

The emitter electrode length is preferably less than approximately 200μm, more preferably, between approximately 50μm and approximately 200μm, and most preferably, between approximately 50μm and approximately 100μm.

An electrical insulator may be disposed between non-interacting portions of the emitter electrode and collector electrode. A thermal heat barrier must be included to prevent heat loss from the source. The thermal heat barrier can be selected from alumina, quartz, aerogel, a multifoil system or a microheat barrier system. In the microheat barrier approach, multiple, highly-reflective surfaces are separated by micro-spikes or micro-posts and are fabricated using microfabrication techniques.

The preferred temperature for operation for the present invention is between approximately 850K and approximately 1200K. More preferably, the temperature is between approximately 1100K and approximately 1200K.

The present invention is also directed to a self-powered microthermionic converter with a diode having a collector electrode and an emitter electrode, a fuel cup, a thermal power source within the fuel cup and an interelectrode gap spaced between the emitter electrode and an edge region outside of the fuel cup. The outer surface of the fuel cup is coated with a thermionic electron emissive layer to form the emitter electrode. The edge region is coated with a thermionic electron emissive layer to create a collector electrode. The diode of the embodiment is in electrical contact with an electric circuit.

The present invention also includes methods for thermionic power conversion by placing an incorporated thermal power source in thermal contact with an emitter electrode. The heated emitter electrode emits electrons which travel across a micron

spaced interelectrode gap to a collector electrode. Upon reaching the collector electrode, the electrons flow through an external resistive load that may be integral to the same micro-chip housing the self-powered thermionic device, or that may be external to the self-powered thermionic device. After traveling through this load, the electrons return to the emitter electrode, thereby completing an electrical circuit. The method can include utilization of an incorporated thermal power source where the source is enclosed within the emitter electrode.

The present invention further includes a method for manufacturing the self-powered microthermionic converter apparatus. A thermally and electrically insulating material is used as a substrate and forms a fuel cup with a thermal power source from the substrate through micromachining techniques. At least one thermionic electron emissive layer is deposited on the outer surface of the fuel cup to comprise an emitter electrode. A collector electrode is formed within the substrate outside of the emitter electrode by depositing at least one layer of a thermionic electron emissive material on at least one wall of the substrate. The thermionic electron emissive layer or layers are preferably formed through chemical vapor deposition techniques (CVD). CVD is preferred for non-planar geometries, however, RF sputter deposition, physical vapor deposition, reactive deposition, laser ablation, or electrophoretic deposition can be used, as well. A micron spaced interelectrode gap is located between the collector electrode and emitter electrode. Micromachining techniques are preferably used to form the fuel cup and substrate wall utilized as the collector electrode surface. The converter is preferably incorporated into a micromachined wafer.

The method of the present invention also comprises forming a fuel cup by forming a fuel grid, aligning the grid with the cups, inserting the sources in the cups, capping the cups, and dissolving the grid. The cap is preferably made of a highly reflective surface, non-reactive metal, such as gold.

A primary object of the present invention is to provide a mobile, miniature, self-powered thermionic converter.

Another primary object of the invention is to provide a thermionic power source of reduced size for incorporation into the converter.

Another object of the invention is to increase the efficiency of a thermionic converter by reduction in size of the interelectrode gap to micron-scale.

A primary advantage of the present invention is the small size of the invention due to the incorporation of a radioisotopic thermal heat source, which need only be utilized in minute amounts, and has a relatively long lifetime (e.g., months). The incorporation of the source removes the need for the external heat sources necessary with prior art devices. This both increases the mobility and decreases the necessary size of the converter in combination with the heat source.

Another distinct advantage of the current invention is the incorporation of the thermionic converter directly into the chip or other device it is intended to power. Such chips or devices can include MEMS, IMEMS, and micro fuel cell devices.

Other objects, advantages and novel features, and further scope of applicability of the present invention will be set forth in part in the detailed description to follow, taken in conjunction with the accompanying drawings, and in part will become apparent to those skilled in the art upon examination of the following, or may be learned by practice of the invention. The objects and advantages of the invention may be realized and attained by means of the instrumentalities and combinations particularly pointed out in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated into and form a part of the specification, illustrate one or more embodiments of the present invention and, together with the description, serve to explain the principles of the invention. The drawings are only for the purpose of illustrating one or more preferred embodiments of the invention and are not to be construed as limiting the invention. In the drawings:

Fig. 1 is a graph showing the predicted current density, J, and power density, P_{den}, for the converter in relation to temperature in degrees Kelvin at the emitter

electrode (these predictions were made using an analytic model that correctly includes thermionic emission and heat transfer effects, including thermal losses);

Fig. 2 is a graph depicting device efficiency, η, for the converter in relation to temperature in degrees Kelvin at the emitter electrode;

Figs. 3(a)-3(f) schematically illustrate an example of steps for fabricating a microspike wafer, according to the present invention;

Figs. 4(a)-4(b) schematically illustrate an example of steps for fabricating collector wafer 10, according to the present invention.;

Figs. 5(a)-5(b) schematically illustrate an example of steps for fabricating an upper assembly according to the present invention;

Figs. 6(a)-6(g) schematically illustrate an example of steps for fabricating a fuel cup in an emitter wafer, according to the present invention;

Figs. 7(a)-7(c) schematically illustrate an example of steps for fabricating a lower assembly by inserting multiple thermal fuel sources into fuel cups, according to the present invention;

Figs. 8(a)-8(d) schematically illustrate an example of steps for assembling the self-powered microminiature thermionic converter by combining the upper and lower assemblies, according to the present invention;

Fig. 9 schematically illustrates a completely assembled self-powered microthermionic convertor, according to the present invention;

Fig. 10 shows a scanning electron microscope image of a 1 micron tall GaAs microspike with a sharp, cusp-like tip, according to the present invention; and

Fig. 11 shows a scanning electron microscope image of a hexagonal array of 3 micron tall GaAs microspikes with sharp, cusp-like tips, made by high temperature reactive ion beam etching, according to the present invention.

DETAILED DESCRIPTION OF THE INVENTION

Microthermionic converters of the present invention are manufactured using semiconductor integrated circuit (IC) fabrication methods and bulk or surface micromachine manufacturing techniques. All elements of the diode (emitter electrode, collector electrode) are made using standard chemical vapor deposition techniques and etch techniques known by those skilled in the art in the semiconductor industry. Chemical vapor or physical deposition allows for accurate, reproducible crystalline growth of extremely thin layers of metals or oxides (for electrode formation).

The microthermionic converter is fabricated with an interelectrode gap space of preferably less than 10μm, more preferably between approximately 1μm and 10 μm, and most preferably between approximately 1μm and 3μm, by utilizing microengineering techniques, thereby allowing the converter to be operated without significant performance penalty due to space-charge effects; in the absence of typically utilized high pressure cesium vapor system. These techniques are thoroughly detailed in the '858 patent to King, et al.

Unlike more common thermionic devices that utilize a high pressure cesium vapor system in the interelectrode gap (IEG), the present invention can utilize vacuum conditions within the interelectrode gap while still maintaining flow of electrons, without significant space-charge effect interruption of flow. The present converter achieves this with its micro-engineered micron-spaced interelectrode gap. Herein, the phrase "micron-spaced interelectrode gap" refers to an interelectrode gap of preferably less than 10μm, more preferably between approximately 1μm and 10 μm, and most preferably between approximately 1μm and 3μm.

Alternatively, the microthermionic converter can utilize an encapsulated, low pressure Cs or Ba vapor system in its interelectrode gap using a refractory, high-work function metal as a substrate for the thermionic electron emissive material. When using a low pressure, Cs or Ba vapor system, the Cs or Ba atoms will adsorb onto the electrode's metal surface, producing a lowered work function for the electrode.

The thermionic electron emissive materials utilized by the converter preferably include an alkaline earth oxide in combination with a refractory metal and adjunct oxides. Candidate alkaline earth oxides include barium, calcium and strontium oxides, combinations of these oxides, along with additions of aluminum and scandium oxides, as adjunct oxides. Refractory metals can be incorporated into the thermionic electron emissive oxide or mixture of oxides to facilitate thermochemistry. Candidate metals include tungsten, rhenium, osmium, ruthenium, tantalum, and iridium, or any combination of these metals. These mixtures are low work function materials (i.e., less than 2.5 eV). Use of these materials solely or in combination with higher work function terminating (capping) layers (e.g. tungsten, rhenium, scandium, ruthenium, osmium, iridium) allow the converter to be operated at lower temperatures than the typically used refractory metals, with higher work function, e.g., tungsten and molybdenum, as the solely utilized thermionic electron emissive materials. High work function refractory metals and their oxides can be used in combination with a low-pressure cesium or barium vapor to produce lower temperature, electron emissive electrodes.

Researchers at Philips (Aachen, Germany) have used rhenium and scandium oxide deposition on a macro-dispenser cathode that resulted in a work function of 1.2 eV and an emission coefficient of 8 $A \cdot cm^{-2}K^{-2}$.

We have produced a thin film version of an electron emissive material comprising scandium oxide capped barium, strontium, calcium oxide that has a work function of 1.2 eV and an emission coefficient of 70 $mA \cdot cm^{-2}K^{-2}$.

Thermionic electron emissive electrodes can be fabricated in thin film form by either co-depositing or sequentially depositing alkaline earth oxides, adjunct oxides and metals. Co-deposition allows for a finely dispersed heterogeneous mixture of oxide, adjunct oxide, and metal to facilitate subsequent thermochemistry. Alternately, multilayer films can be deposited to allow for a more coarsely dispersed heterogeneous mixture of oxide, adjunct oxide, and metal. A multilayer film allows for the selective termination (capping) of the thermionic electrode. Deposition techniques include chemical vapor deposition (CVD), RF sputter deposition, physical vapor deposition,

reactive deposition, laser ablation, electrophoretic deposition, or combinations of these techniques. CVD could be used to deposit the alkaline earth oxide using barium hydroxide, to deposit an adjunct oxide like scandium oxide using scandium acetylacetonate, and a refractory metal like tungsten using tungsten hexafluoride, where the hydroxide, acetylacetonate, and hexafluoride represent volatile precursors suitable for an elevated temperature CVD process. RF sputter deposition can be used deposit both co-deposited and sequentially deposited films using a multi-target system with separate targets made form the emissive oxide, the adjunct oxide, and the desired metals. An example of a multilayer thermionic electron emissive film is a composite structure comprised of stacked layers of a mixed barium, strontium, and calcium oxide and scandium oxide on top of tantalum deposited onto a silicon wafer. The estimated work function of this combination is 1.7 eV. Alternately, the thermionic electron emissive materials can be comprised of modulated layers of a mixed barium, calcium, strontium oxide or a mixed barium, calcium, aluminum oxide with tungsten and scandium oxide. These compositionally modulated films have work functions of less than 2 eV and emission coefficients of greater than 20 $A \cdot cm^{-2}K^{-2}$.

The emitter and collector electrodes may be comprised of different, or the same, thermionic electron emissive material. Additionally, the work function or emission coefficients of the emitter and collector electrodes may be the same, or different.

The self-powered thermionic converter of the present invention incorporates a radioisotopic thermal power source. Curium-242 (or Cu-244) is particularly well suited as a heat source. It emits an alpha particle during radioactive decay at a rate sufficient to provide an acceptable thermal power density (1170 W/g), and has a sufficiently long half-life (i.e., 163 days for Cu-242 and 17.6 years for Cu-244) to provide sustained power. Other radioisotopes known in the art such as Polonium-210 (half-life = 138 days, thermal power density = 1320 W/g) can also be utilized in the present invention.

Heat from the spontaneous decay of the radioisotope is conducted to the emitter electrode, resulting in thermionic emission of electrons from the emitter surface. These

electrons cross the vacuum interelectrode gap and are collected by the cold collector electrode. The electrons then return to the emitter electrode through an external electrical load connected in series to the electrodes, thereby providing electrical power to that external load. With the micron-scale size of the converter, the entire unit can be incorporated into the circuitry of the external load device, thereby easily incorporating the electricity generating thermionic converter into the device it operates.

The preferred range for a typical emitter dimension (length, diameter, etc.) is 50-200 microns, with a most preferred range of 50-100 microns. Heat from the spontaneous decay of a radioisotope is conducted to an emitter electrode, resulting in thermionic emission of electrons from the hot emitter surface. A thermal heat barrier is used in the converter to minimize heat loss from the thermal power source. Heat barrier materials such as alumina, quartz, and aerogel may be utilized in the converter, however, highly effective micro heat barriers are preferred.

Simple thermal and thermionic electron emission models can determine the design and operation characteristics. These models give a projected performance of a device utilizing a particular isotope. The graphs in Figs. 1 and 2 are predictions based on a thermal/thermionic analytical model for a Curium-242 radioisotope, demonstrating that the predicted power density, P_{den} (W/cm^2), and current density, J (A/cm^2), optimize for such a converter when the T_E, or emitter temperature, is within the range of 1100 - 1200K. Additionally, the percent efficiency, η (%), of the converter optimizes within that same range, 1100 -1200K. Finally, for this prototype design, the length of the emitter L_E is optimal within a range of 50-200 μm, with a preferred range of 50-100μm, at the optimal temperature range. Smaller devices may be possible with improved micro-fabrication techniques.

Figs. 3(a)-3(f) schematically illustrate an example of a method for fabricating a microspike wafer **12**, according to the present invention. Collector wafer **10** and microspike wafer **12** are combined to form upper assembly **14**. Microspike wafer **12** is utilized in both upper and lower assemblies of the preferred embodiment to act as a microheat barrier (i.e., microfoil insulation). Microspike wafer **12** can include multiple layers of microfoil (e.g., 2-12 layers), depending on the amount of thermal insulation

required, which may vary in relation to the radioisotope utilized. Chemical vapor deposition techniques are preferably used to deposit various layers of material of which the elements of the thermionic converter are comprised.

In Fig 3(a) a microspike wafer 12 is fabricated by growing (i.e., depositing) a first epitaxial layer **18** (i.e., AlGaAs) on a first substrate wafer **8**. First epitaxial layer **18** serves as a "stop layer" useful when etching. First substrate wafer **8** is substantially flat and comprises a dielectric material (i.e., GaAs or silicon). In Fig 3(b) a second epitaxial layer **18** (i.e., GaAs) is grown on top of the first epitaxial layer **16**. Next, in Fig. 3(c) the second epitaxial layer **18** is patterned and etched to form microspike array **20** using micromachining techniques. Then, in Fig. 3(d), a protective layer of photoresist **22** is deposited over spike array **20**. Next, in Fig. 3(e), first wafer **8** is inverted and then patterned and etched down to stop layer **18** through micromachining techniques to form first recess **27**. Then, in Fig. 3(e), a highly reflective layer **24** is deposited over the pattern.

Highly reflective layer **24** can comprise a film of gold that is deposited by thermal evaporation, sputtering, electrodeposition, or chemical deposition. Other infrared reflective (IR) materials can be used, including platinum, titanium, or combinations thereof. Alternatively, the infrared reflective layer **24** can comprise a laminated stack of two alternating layers of IR transparent materials, where one material has a large difference in its index of refraction relative to the other. For example, highly reflective layer **24** can comprises four laminated layers of two alternating materials; a low index material (e.g., SiO_2, n = 1.5), and a high index material (e.g., TiO_2, n = 2.4). An example of a 4-layer HR stack can comprises $TiO_2/SiO_2/TiO_2/SiO_2$. The thickness of each layer in the HR stack can vary, depending on its particular location in the stack.

Finally, in Fig. 3(f) gas escape (or contact hole) **26** is cut into highly reflective layer **24** and stop layer **18**, thereby completing formation of microspike wafer **12**.

Microspike wafers comprising microspikes and one or more IR reflecting layers (e.g., microfoils) are preferably used for prevention of heat loss. The spike array can have its tips directed toward the thermal source location to minimize potential thermal contact. The shape of the spike can be cusp-like, with a sharp, pointed tip. This

configuration aids in preventing heat loss. Alternatively, the cross-section shape of a microspike spike can be conical, pyramidal, or cylindrical. Multiple layers (e.g., 2-12) of infrared reflective layers or microfoils can be fabricated and stacked on top of one another to increase the effective thermal resistance.

Figs. 4(a)-4(b) schematically illustrate an example of the steps for fabricating collector wafer **10**, according to the present invention. In Fig. 4(a) collector wafer **10** is prepared by cutting hole **28** in second substrate wafer **30** having a substantially flat surface and comprising a dielectric. Second substrate wafer **30** can comprise the same materials as first substrate wafer **8**, e.g., GaAs, depending on the requirements of the specific device. Next, in Fig. 4(b), thermionic electron collector material is deposited along internal wall **34** of hole **28** to make collector electrode **32**. Internal wall **34** may comprise multiple walls arranged in a complex geometric form or a single curved wall depending on the machining technology utilized. Electrical trace **9** is deposited on the surface of wafer **30**, and makes electrical contact with collector electrode **32**

Low work function materials useful in the present invention include barium, calcium and strontium oxides, mixtures of these oxides, along with additions of aluminum and scandium oxides, as adjunct oxides. Metals, such as tungsten, rhenium, osmium, ruthenium, tantalum, and iridium, or any combination of these metals, may be deposited into or on top of the mixture. Metal electrode materials, such as tungsten, molybdenum, tantalum, or their oxides can be used in conjunction with a cesium or barium vapor.

Next, in Fig. 5(a), collector wafer **10** is aligned and then bonded to the microspike array side of microspike wafer **12**. This forms upper assembly **14**, as shown in Fig. 5(b).

Figs. 6(a)-6(g) illustrate schematically an example of the steps for fabricating fuel cup **36** in emitter wafer **38**, according to the present invention. In Fig. 6(a) stop layer **40** is deposited or grown on third substrate wafer **31**. Next, in Fig. 6(b) stop layer **40** is patterned, and then highly reflective layer **25** is surface deposited within the pattern on top of stop layer **40**. Next, in Fig. 6(c), wafer **31** is inverted, patterned, and

etched along the patterns to form fuel cup base **42**. Next, in Fig. 6(d), thermionic electron emissive material is deposited on the etched surface of wafer **38** to make emitter electrode **33**, and excess is removed through mask and micromachining techniques. The excess areas removed include all areas except outside wall **44** of fuel cup base **42**. Next, in Fig. 6(e), the side of emitter wafer **38** with reflective layer **25** is aligned with and then bonded to the microspike array side of a second microspike wafer **12′** to form the assembly shown in Fig. 6(f). Next, in Fig. 6(g), fuel cup **36** is formed by removing third substrate wafer **31** material from inside of fuel cup base **42**. Excess wafer material **31** is also removed. Finally, stop layer **40** is selectively removed to complete formation of fuel cup **36** in emitter wafer **38**, thereby forming fuel cup assembly **53**. Alternatively (not illustrated), fuel source **48** can be deposited into a long, narrow trench, instead of a cylindrical cup **36**. Emitter coating **33** and thermionic emissive materials would be applied to one or more surfaces of the trench, while maintaining the micron-sized interelectrode gap **76**.

Figs. 7(a)-7(c) schematically illustrate an example of the steps for fabricating lower assembly **54** by inserting multiple thermal fuel sources **48** into fuel cups **36**, according to the present invention. In Fig. 7(a), precision grid **46** is fabricated, through techniques familiar in the art, with dissolvable source buckets **50**. Fuel source **48** is deposited in source buckets **50** by evaporation or sputtering methods (if solid), or by liquid capillary action (if liquid). Highly reflective cap **52** (e.g., gold) is deposited on source **48**. Fuel source **48** is shown in a cylindrical form, however, other shapes can be utilized (e.g., sphere, flat plate, wire, bar, etc). Also, thermionic electron emissive material can be deposited directly on to fuel source **48** (not illustrated). For example, thermionic electron emissive material can be deposited on a spherically shaped fuel source **48**. Other metals that are highly IR reflective may be used as the cap material. Preferably, the cap material is comprised of a non-reactive material with a highly reflective surface to assist in preventing heat loss. Next, in Fig. 7(b), grid **46** is aligned over fuel cup assembly **53** in alignment with fuel cups **36**. Next, source buckets **50** are

inserted into fuel cups **36** and then grid **46** and buckets **50** are dissolved. The insertion step completes the fabrication of lower assembly **54**, as shown in Fig. 7(c).

In Fig. 7(c), heat that is generated in fuel source **48** from capture of radioactive decay particles (e.g., alphas) is primarily conducted out though the bottom of source **48**, then radially outwards inside stop layer **40** and through gold reflective layer **25**, and then vertically up through inner cylindrical shells **42** and emitter electrode **33**. Thermal radiation across the gap (assembly tolerance) between source **48** and wall **42** can also contribute to heating of emitter electrode **33**.

Figs. 8(a)-8(d) schematically illustrate an example of the steps for assembly of the self-powered microminiature thermionic converter by combining upper and lower assemblies **14, 54**, according to the present invention. In Fig. 8(a) upper assembly **14** is aligned with lower assembly **54** such that full fuel cups **36** are inserted into holes **28** of collector wafer **14**. Assemblies **14** and **54** are bonded by their joined faces, producing the assembly shown in Fig. 8(b). Micron-sized interelectrode gap **76** is defined by the outer diameter of emitter electrode **33** and the inner diameter of collector electrode **32**. Next, in Fig. 8(c) photoresist layers **22, 22´** of upper and lower assemblies **14, 54** are dissolved. Next, in Fig. 8(d) upper wafer **8** is lapped and thinned. Also, bottom plate **72** is attached to the lower side of lower wafer **8´**, thereby forming gas collection chamber **70** (e.g., for collecting helium gas from alpha particle radioactive decay of fuel source **48**).

Fig. 9 schematically illustrates an example of the present invention completely assembled according to the previously described steps. Electrical contact wire **74** has been attached and inserted through gas escape hole **26** to make electrical contact with highly IR reflective layer **52** disposed on fuel source **48**, which is electrically connected to emitter electrode **33**. Electrical contact wire **74** can comprise an intermittent, charged spring contact. Positive charges build up on the hot emitter electrode due to thermionic electron emission, which electrostatically attracts spring contact element **74** to make electrical contact with emitter electrode **33**. After discharging the positive charge by allowing electrons to flow through contact **74**, the physical contact is broken due to the loss of electrostatic force. Repeated cycles of intermittent contact provides

intermittent current flow, with minimal heat loss when contact **74** is not touching the emitter electrode. Other means for creating an intermittent electrical contact can be provided, such as use of externally-controlled MEMS-type micromechanical actuators (e.g., comb drive, solenoid, etc.), and bi-metallic strips that bend when heated or cooled. Electrons that are emitted thermionically from emitter electrode **33** travel across the interelectrode gap **76** and are collected by collector electrode **32**, whereupon the collected electrons travel through electrical trace **9** to the electrical load, and then back through wire **74** to return to emitter electrode **33**, thereby creating a closed electrical circuit.

Variations and modifications of the present invention will be obvious to those skilled in the art and it is intended to cover in the appended claims all such modifications and equivalents.

Fig. 10 shows a scanning electron microscope image of a 1 micron tall GaAs microspike with a sharp, cusp-like tip, according to the present invention.

Fig. 11 shows a scanning electron microscope image of a hexagonal array of 3 micron tall GaAs microspikes with sharp, cusp-like tips, made by high temperature reactive ion beam etching, according to the present invention.

The entire disclosures of all references, applications, patents, and publications cited above are hereby incorporated by reference.